Predicting soil water content at – 33 kPa by pedotransfer functions in stoniness 1 soils in northeast Venezuela

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Abstract

Soil water content is a key property in the study of water available for plants, infiltration, drainage, hydraulic conductivity, irrigation, plant water stress and solute movement. However, its measurement consumes time and, in the case of stony soils, the presence of stones difficult to determinate the water content. An alternative is the use of pedotransfer functions (PTFs), as models to predict these properties from readily available data. The present work shows a comparison of different widely used PTFs to estimate water content at-33 kPa (WR_{-33kPa}) in high stoniness soils. The work was carried out in the Caramacate River, an area of high interest because the frequent landslides worsen the quality of drinking water. The performance of all evaluated PTFs was compared with a PTF generated for the study area. Results showed that the Urach's PTF presented the best performance in relation to the others and could be used to estimate WR_{-33kPa} in soils of Caramacate River basin. The calculated PTFs had a R^2 of 0.65. This was slightly higher than the R^2 of the Urach's PTF. The inclusion of the rock fragment volume could have the better results. The weak performance of the other PTFs could be related to the fact that the mountain soils of the basin are rich in 2:1 clay and high stoniness, which were not used as independent variables for PTFs to estimate the WR_{-33kPa}.

Keywords

Multiple linear regression
Particle size distribution
Soil stoniness
Soil water content

Introduction

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The determination of soil water content (θ) at field capacity (FC) is complex and in particular in stony soils. Consequently, the amount of water retained at the tension of − 33 or − 10 kPa are frequently used, assuming it is equal to the FC (Cong et al. 2014; He et al. 2015; Ali Ghorbania et al. 2017). Although this limit is arbitrary, this represents an alternative to conduct assessments in a simple and practical way (Pineda and Viloria 1997). The field capacity is used as a reference value for application related to agriculture and water and soil resources management (Rao 1998). The use of this soil water retention value still leaves a problem to solve: the time needed for the measurements (Botula et al. 2014). Therefore, an alternative is an indirect estimation using available soil data (Zhuang et al. 2001). This has raised the interest to develop pedotransfer functions as models to predict soil water retention properties from routine and easy to obtain data (Pineda and Viloria 1997; McBratney et al. 2002), such as soil texture (sand, silt, and clay content), bulk density (Bd), soil organic matter (SOM) or soil organic carbon (SOC), and/or other data registered in soil surveys (Bastet et al. 1999; Al Majou et al. 2007, 2008a, b; Baker 2008; Botula et al. 2014; Nasri et al. 2015). The term pedotransfer functions was introduced by Bouma and Van Lanen (1987) as predictive functions of certain soil properties from other characteristics which are less costly or laborious to measure. Several moisture retention models have been validated with large amounts of data (Pidgeon 1972; Lal 1979; Arruda et al. 1987; Dijkerman 1988; Bell and Van Keulen 1995; Pineda and Viloria 1997; Tomasella and Hodnett 1998; Oliveira et al. 2002; Peraza 2003; Reichert et al. 2009).While it has been attempted to apply models to estimate soil water retention universally, it has been seen that PTFs models perform better in the area where they were developed than when they are used in other areas (Pineda and Viloria 1997; Nebel et al. 2010). For this reason is necessary to have caution in the application of PTFs outside the area of development (Patil and Singh 2016).

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When using pedotransfer functions, two approached can be considered. In the first, the models are used to estimate soil properties, such as available water capacity. In the second, the predicted soil properties are used as inputs for simulation or for decision-support models. On the other hand, PTFs represent an alternative when there is not enough budget and/or time, considering that the spatial and temporal variations of soil properties increase the number of measurements (Abbasi et al. 2011). Because of that, the development of PTFs should be an integral part of soil information systems (Patil and Singh 2016).

The choice of adequate PTF for a particular region and/or for particular soil types is essential for the accuracy of the estimations (Medeiros et al. 2014). Most of the PTFs have been developed for soils under temperate conditions, and little research has been carried out for the prediction of soil properties in the tropics, where the need for accurate and up-to-date soil information is very important and urgent (Minasny and Hartemink 2011). In the tropics, efforts to improve the way of determining soil moisture content with greater accuracy and precision are being done. However, the development of PTFs for soil different types is still limited. Particularly for stony soils, PTF to predict Ks (Nasri et al. 2015) or field capacity have not been published.

Multiple linear regression is the most common used techniques for deriving PTFs for single point estimation (Liao et al. 2011; Botula et al. 2014). In Venezuela, multiple regression equations have been developed to predict soil water content at − 33 and − 1500 kPa in representative soils of the Western Plains (Delgado and Barreto 1988), in alluvial soils of the Valencia Lake basin (Pineda and Viloria 1997), and in other tropical regions (Tomasella and Hodnett 1998). However, these studies do not include soils with high stoniness (rock fragments) in their profile. Stony soils are soils containing over 35 or 40% in volume of soil particles larger than 2 mm (Soil Survey Staff 2010).

The presence of stones and gravels in soils may modify the physical properties and hydrological functions, such as water storage, infiltration, and evaporation; and soil hydraulic properties such as hydraulic conductivity and water retention capacity (Van Wesemael et al. 1996; Ma and Shao 2008; Coppola et al. 2011). For example, the saturated hydraulic conductivity can be decreased with increasing stone contents or increased for increasing stone content (Khetdana et al. 2017; Nasri et al. 2015). In turn, water availability for plants is reduced, limiting plant water consumption, biomass, and growth (Mi et al. 2016). Although the influence of rock fragments on these properties is recognized, the study of water retention in stony soils has been often ignored (Tetegan et al. 2015; Nasri et al. 2015).

The presence of rock fragments difficult the measurement of soil water content in the field due to practical problems. The values obtained usually require adjustments, depending on the content of coarse fragments (Coppola et al. 2013) and the characteristics related to rock fragments (Tetegan et al. 2011). Tetegan et al. (2015) and Mi et al. (2016) showed that the water content may be overestimated or underestimated when it is assumed that soil is completely constituted by the fine fraction or not. Additionally, stony soils require specific sampling techniques (Büchter et al. 1984).

The abovementioned problems, lack of detailed soil data and the presence of stoniness soils, are common characteristics in areas of the Central Coast Range of Venezuela. One of these areas, which is part of an important watershed, was selected as a study area of the present research (part of the Caramacate River Basin). This area represents the main water source for both human consumption and agriculture irrigation in the region. In this respect, the objective of the present work was to evaluate existing pedotransfer functions to estimate soil water content at − 33 kPa, to determine their applicability to estimate the soil water content in the study region. The results were compared with a PTF generated in the study area.

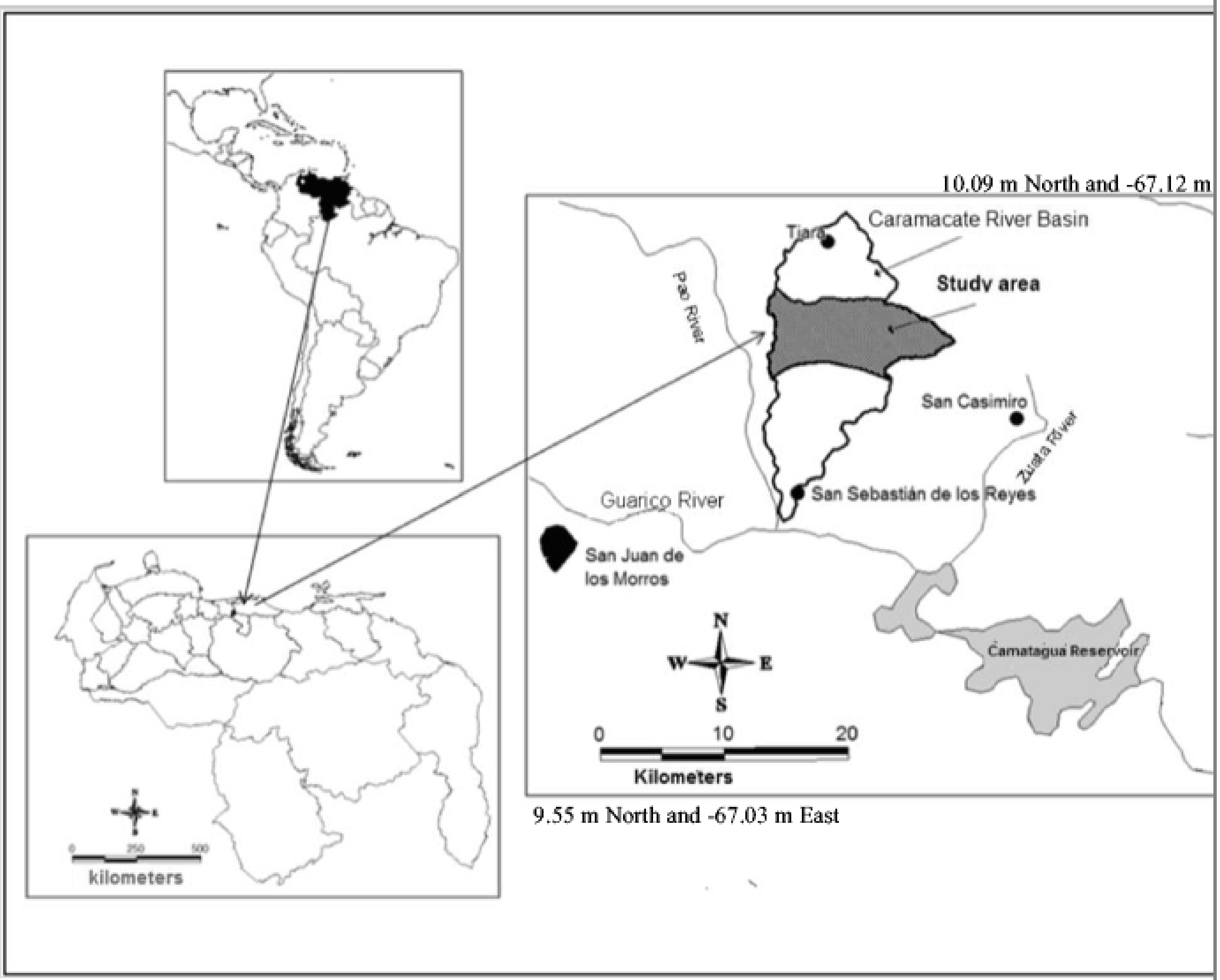
Materials and methods

Study area

The study area comprises of 6760 ha of the Caramacate River Basin (Fig. 1), located in the south of the Central Coast Range of Venezuela (10° 20 North and 67° 70 West, approximately). The terrain is hilly, with elevation ranging from 334 to 1405 masl. and a mean slope about 40%. The mean annual rainfall is 1100 mm, and the mean annual temperature is 22 °C (Pineda et al. 2011). According to Urbani and Rodriguez (2003), lithology is represented by rocks of Villa de Cura Group. Soils are mostly Entisols, Inceptisols, and Alfisols of loam texture, with an ustic moisture regime (Soil Survey Staff 2010). The soils are shallow due to the occurrence of landslides; for this reason, the sequence of horizons found most frequently is A/C, has high contents of rock fragments (> 2 mm), increases in clay content with depth, although, and has good structural stability (average diameter of pores). These soils are rich in 2:1 clays (vermiculite and smectite). Some of them are very or extremely stony on the surface. They are generally well-drained soils and have moderate permeability (Pineda et al. 2011). The dominant vegetation is herbaceous (*Hyparrhenia rufa)*, subjected to extensive grazing systems.

Fig. 1

Location of the Caramacate River basin (Venezuela) and the study area



Soil data

Ninety-seven soil profiles randomly located were described and sampled in the study area. At each sampling site, disturbed and undisturbed samples were extracted from the surface horizon (between 0 and 22 m) to determine the soil properties (Table 1). The undisturbed samples were taken with an Uhland type sampler, using cylinders of 7.5 cm high and 7.5 cm in diameter (313.9 cm^3). The sampling was done in areas under herbaceous vegetation and shallow soil.

Table 1

Soil properties analyzed at each sampling point

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Property of the soil	Symbol	Method of determination
Clay (%)	Clay	Pipette method (Gee and Or 2002)

Property of the soil	Symbol	Method of determination
Sand (%)	Sand	Pipette method (Gee and Or 2002)
Rock fragments volume (%)	RFV	Volumetric displacement (McCormack et al. 1982)
Water content at − 33 kPa (kg kg^{-1})	WR-33 kPa	Pressure plates (Richards 1948)
Bulk density (Mg m^{-3})	Bd	Cylinder method (Grossman and Reinsch 2002)
Soil organic carbon (%)	SOC	Walkley and Black modified (Heanes 1984)

The presence of stones introduces difficulties for indirect and direct water content measurements. The water content measure by TDR probes (Coppola et al. 2013) presented practical issues for inserting probes due to the fact that it is impossible to introduce these without altering the soil structure.

The direct water content measure is a difficult method, due to the characteristics of the study area. This is an area of difficult access; the terrain is hilly with a slope of about 40%. For this reason, the gravimetric water content to FC was determined in cylinders of samples not altered in the laboratory, which did not evaluate the effects of possible limitations in the internal drainage by effect of different strata in the profile of the soil, nor the lateral loss of water.

The percentage of stoniness in volume was determined, with a diameter greater than 2 mm in each cylinder, following the methodology of McCormack et al. (1982).

Application of existing PTFs to estimate soil water retention

Twelve existing PTFs were used to estimate soil water content at − 33 kPa ($WR_{-33\ kPa}$) (Table 2). These functions were selected because of their specificity to determine WR. However, most of these PTFs were developed for other regions and for a limited range of soil textures (Table 2). The behavior of the PTFs was evaluated based on the mean error (ME, Eq. 1), the root mean square error (RMSE, Eq. 2), and the coefficient of determination (R^2) between the observed and predicted values (Xiangsheng et al. 2013). The same parameters were used by Nebel et al. (2010) and by other different researchers to evaluate and validate PTFs (Patil and Singh 2016).

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$$ME = \frac{1}{n}\sum\nolimits_{i=1}^{n}(ei - m1)$$

$$RMSE = \sqrt{\frac{1}{n}\sum\nolimits_{i=1}^{n}(ei - m1)^{2}} \tag{2}$$

Table 2

Selected pedotransfer functions (PTFs) derived from soil data sets and evaluated in this study

Authors	PTFs
Pidgeon (1972)	$WR_{-33\ kPa}$ [a] = (0.0361 + (0.0016 × silt[b]) + (0.003 × clay[c]) + (0.03 × SOC[d]))/0.95 Region: ferralitic soil in Uganda (two soils of alluvial deposits with kaolinite and one with montmorillonite)
Lal (1979)	$WR_{-33\ kPa}$ = 0.334 − (0.003 × sand[e]) Region: 23 soil profiles in southern Nigeria with 119 samples
Arruda et al. (1987)	$WR_{-33\ kPa}$ = (3.07439 + (0.629239 × (silt + clay)) − (0.00343813 × (clay + silt)^2))/100 Region: several highland agricultural soils in the Sao Paulo State, Brazil
Dijkerman (1988)	$WR_{-33\ kPa}$ = (36.97 − (0.35 × sand))/100 Region: soils from Sierra Leona, West Africa, catena of 13 soils units
Delgado and Barreto (1988)	$WR_{-33\ kPa}$ = (29.06 − (0.29 × sand) − (0.253 × silt) + (0.135 × clay) + (2.56 × SOM[f]) Region: soil samples representative of the Western Plains, Venezuela
Bell and Van Keulen (1995)	$WR_{-33\ kPa}$ = (48.7 + (0.9748 × SOM) − (28.3 × Bd) − (0.14 × clay))/100 Region: soils from four contrasting agro-ecological environments in Mexico

WR : gravimetric soil water content (kg kg) at the matric potential of − 33 kPa; Silt: silt content (%); Clay: clay content (%) ; SOC: soil organic carbon content (g kg); Sand: sand content (%); SOM: soil organic matter content (g kg); Bd: soil bulk density (Mg m) 1~~bSilt: silt content (%)~~
Silt: silt content (%)
Clay: clay content (%)
SOC: soil organic carbon content (g kg)
Sand: sand content (%)
SOM: soil organic matter content (g kg)
Bd: soil bulk density (Mg m)

Authors	PTFs
Tomasella and Hodnett (1998)[1]	$WR_{-33\ kPa} = (4.046 + (0.426 \times silt) + (0.404 \times Clay)$ Region: Brazilian soils
Oliveira et al. (2002)	$WR_{-33\ kPa} = (0.0000333 \times silt) + (0.0000387 \times clay)$ Region: 98 soil sites in the Pernambuco State, Brazil
Peraza (2003)	$WR_{-33\ kPa} = 0.01188 + (0.00002769 \times clay) + (0.00002336 \times silt) + (0.00246 \times SOM)$ Region: 34 soil mapping units in the Rio Grande do Sul State, Brazil
Rawls et al. (1982)[1]	$WR_{-33\ kPa} = (25.76 - (0.2 \times sand) + (0.36 \times clay) + (2.99 \times SOM)$ Region: 1323 soils from about 5,320 horizons from 32 States in the USA
Urach's PTF (Reichert et al. 2009)	$WR_{-33\ kPa} = 0.643 - (0.00238 \times sand) - 0.26767 \times Bd^{g}$ Region: 725 samples of various representative soil classes and horizons in different regions of the Rio Grande do Sul state (Brazil)
Pineda and Viloria (1997)	$WR_{-33\ kPa} = 57.550 + 1.405\ (SOC) - 0.559\ (sand)$ Region: 444 horizons of the Valencia Lake basin, Venezuela
[a]$WR_{-33\ kPa}$: gravimetric soil water content (kg kg^{-1}) at the matric potential of − 33 kPa; [b]Silt: silt content (%);[c]Clay: clay content (%) ;[d]SOC: soil organic carbon content (g kg^{-1});[e]Sand: sand content (%);[f]SOM: soil organic matter content (g kg^{-1});[g]Bd: soil bulk density (Mg m^{-3}) 1~~bSilt: silt content (%)~~	
[b]Silt: silt content (%)	
[c]Clay: clay content (%)	
[d]SOC: soil organic carbon content (g kg^{-1})	
[e]Sand: sand content (%)	
[f]SOM: soil organic matter content (g kg^{-1})	
[g]Bd: soil bulk density (Mg m^{-3}) **1**	

where *ei* is the estimated $WR_{-33\ kPa}$ values, and *m1* is the measured $WR_{-33\ kPa}$ values. ME is an indicator of the accuracy of the estimate that reveals the PTF tendency of the function to overestimate the values whenever these are positive, or underestimate if they are negative. RMSE quantifies the dispersion of the measured and estimated values with respect to the 1:1 line. Based on these indicators, the PTFs were ranked according to the least absolute values of ME, RMSE, and the highest value of R^2 (Nebel et al. 2010).

Development of a PTF to estimate the soil water content in the study area

In addition to applying existing PTFs, a specific function for the study area was also developed. For that, an exploratory analysis of soil data was performed, determining its distribution, central tendency, statistical dispersion, and the presence of outliers. The outliers were identified according to the method of Tukey (1977). This method considers observation Y an outlier if: Y < (Q1 − 1.5 IQR) or Y > (Q3 + 1.5 IQR) where Q1 = lower quartile, Q3 = upper quartile, and IQR = (Q3 − Q1) is the interquartile range. A non-parametric Kolmogorov-Smirnov test was conducted to assess normality of data sets. The Pearson linear correlation analyses were carried out between the soil water content at matric potential of − 33 kPa, and soil characteristics was also calculated. Finally, we performed a multivariate linear regression analysis using the SPSS statistical package to estimate the gravimetric water content ($WR_{-33\ kPa}$), using soil characteristics as independent variables and the water content at matric potential of − 33 kPa as dependent variables. Only those properties that presented the largest correlation coefficients were considered. The behavior of the function was assessed on the basis of the R^2, RMSE, and ME between the observed and predicted values.

Due to the inherent temporal and spatial variability in the determination of water content at field capacity, larger numbers of samples are required to properly characterize the area.

Results and discussion

Estimation of soil water content ($WR_{-33\ kPa}$) using PTFs

The majority of the sampled variables showed a normal distribution tendency (proximity between mean and median values), except for that of rock fragment volume (RFV) (Table 3). Based on the coefficient of variation (CV) classification proposed by Wilding and Drees (1983), data dispersion around their mean was low (CV < 15%) for all variables. For the majority of the variables, the values skewness and kurtosis were close to zero, indicating a good proximity to the normal distribution. This fact was confirmed by the application of the non-parametric test of Kolmogorov-Smirnov (K-S), with most of the variables had a normal distribution (Table 3).

Table 3

Descriptive statistics of all soil attributes used in the evaluated PTFs under analysis

Variables	N	Mean	Median	Min	Max	Std dev	CV	Kurt	Skew	K-S*

Clay	96	19.10	18.55	6.85	38.28	5.94	3.21	−0.44	−0.64	0.76*
Silt	96	48.10	49.27	15.17	78.71	11.75	4.09	−0.15	0.44	0.85*
Sand	96	23.45	22.78	10.47	47.72	7.48	3.14	−0.63	−0.54	0.43*
Bd	78	1.37	1.36	1.11	1.66	0.12	10.94	0.44	−0.06	0.69*
SOM[12]	92	2.92	2.90	1.39	3.83	0.40	7.25	−3.79	0.86	1.20*
$WR_{-33\ kPa}$[10]	86	20.25	21.48	4.67	34.31	6.84	2.96	0.14	0.40	0.43*
$Clay^2$	78	24.66	24.78	14.21	46.25	7.85	3.14	−0.73	−0.28	0.99*
$Silt^2$	78	66.33	66.64	32.79	106.63	18.41	3.60	−0.96	0.63	0.63*
$Sand^2$	78	31.35	32.07	13.32	52.75	9.70	3.23	−0.48	0.27	0.48*
RFV	96	9.35	6.25	0.17	31.99	8.92	1.05	0.36	−0.86	1.57*

N, number of samples; *Mean*, mean value; *Med*, median value; *Min*, minimum value; *Max*, maximum value; *Std dev*, standard deviation; *CV* coefficient of variation (%); *Kurt*, Kurtosis coefficient; *Skew* skewness coefficient; *K-S*, Kolmogorov-Smirnov test; *Bd*, soil bulk density (Mg m^{-3}); *SOM*, soil organic matter content (g kg^{-1}); $WR_{-33\ kPa}$, measured gravimetric soil water content (kg kg^{-1}) at matric potential of − 33 kPa; $Clay^2$, clay content (%) × Bd; $Silt^2$, silt content (%) × Bd; $Sand^2$, sand content (%) × Bd; *RFV*, rock fragments volume (%)

**P* value: 0.05

The assessment of the evaluated PTFs (Table 4) indicated that most of them showed a tendency to overestimate soil water content at − 33 kPa, with the exception of the PTFs by Delgado and Barreto (1988), Bell and Van Keulen (1995), Oliveira et al. (2002), and Peraza (2003), which can be appreciated by the sign of ME. Based on the lowest ME (− 0.01 kg kg^{-1}), the PTF that presented the best performance was the relationship found by Bell and Van Keulen (1995). However, the Urach's PTF (Reichert et al. 2009) presented the highest value of R^2 (62%, Table 4 and Fig. 2). The PTF developed by Delgado and Barreto (1988) presented the lowest RMSE (0.06 kg kg^{-1}, Table 4), showing the lowest dispersion of the measured and estimated values with respect to the 1:1 line.

Table 4

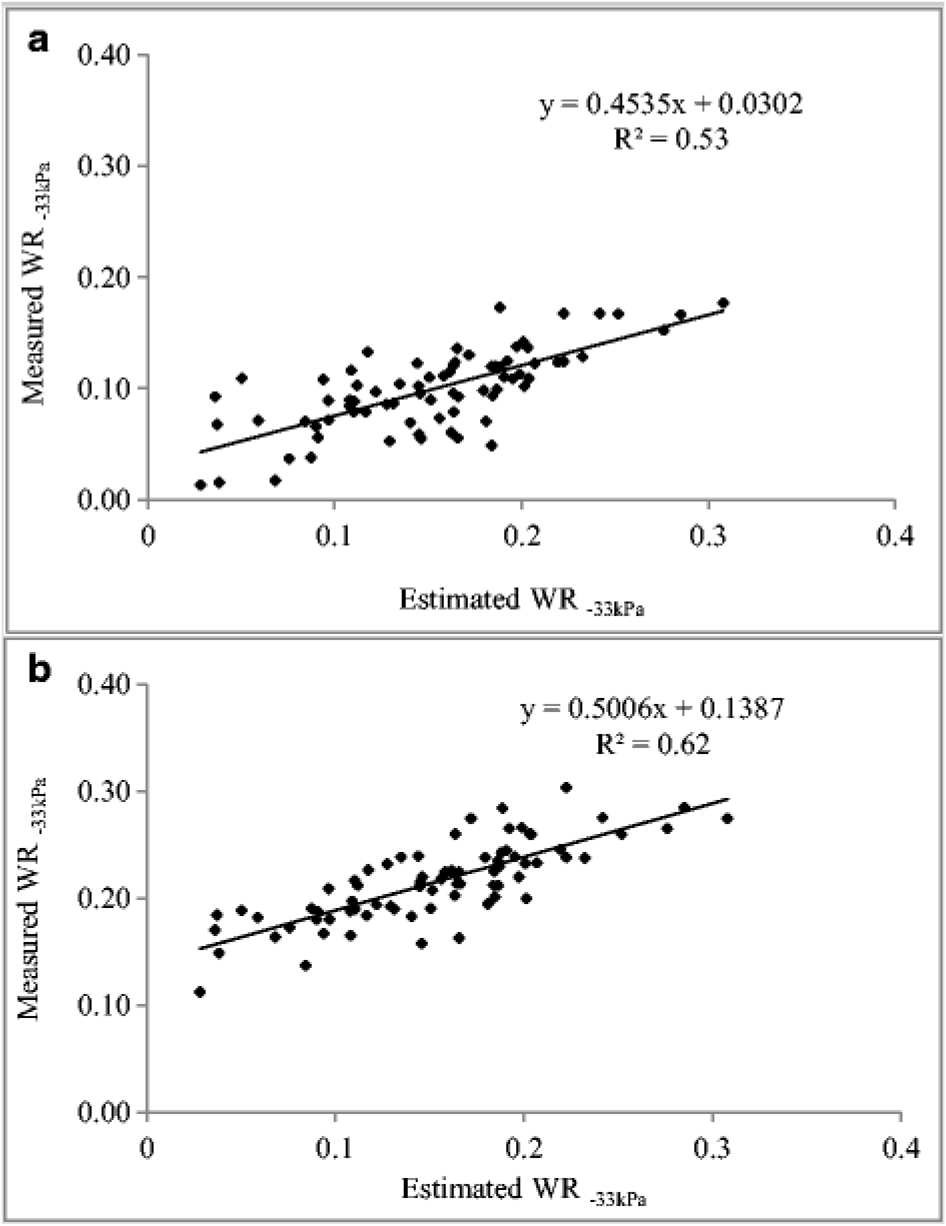
Statistical measures of mean error (ME), root mean square error (RMSE), and coefficient of determination (R^2) used to evaluate the Pedotransfer functions (PTFs) for estimating gravimetric soil water content at matric potential of − 33 kPa

PTFs (author)	ME[a]	RMSE[b]	R^2
Pidgeon (1972)	0.10	0.14	0.00
Lal (1979)	0.11	0.14	0.03
Arruda et al. (1987)	0.16	0.18	0.05
Dijkerman (1988)	0.14	0.16	0.03
Delgado and Barreto (1988)	− 0.02	0.06	0.17
Bell and Van Keulen (1995)	− 0.01	0.17	0.53
Tomasella and Hodnett (1998)[1]	0.09	0.11	0.48
Oliveira et al. (2002)	− 0.13	0.15	0.03
Peraza (2003)	− 0.11	0.13	0.00
Rawls et al. (1982)[1]	0.10	0.12	0.40
Urach's PTF (Reichert et al. 2009)	0.10	0.20	0.62
Pineda and Viloria (1997)	0.30	0.32	0.02

[a, b]Values are expressed in kg kg^{-1}; soil water content (kg kg^{-1}) at the matric potential of − 33 kPa

Fig. 2

Comparison between estimated **a** PTFs of Bell and Van Keulen (1995) and **b** Urach (Reichert et al. 2009) and measured gravimetric soil water contents at − 33 kPa



The lack of fit of the analyzed PTFs in estimating the soil water content could be attributed to the fact that they were generated for other study areas, and its application varies from one region to another (Liao et al. 2011). The soils of the study area had characteristics that considerably differ from the soil characteristics of the areas where the PTFs were developed. This could be the cause of the data dispersion (Fig. 2) and of the low accuracy of water content estimation (Table 4) (Pineda and Viloria 1997; Nebel et al. 2010).

For example, the type of clay determines the amount of water that a soil can retain (Medeiros et al. 2014). Also, it is one of the factors responsible for microstructure formation (Gaiser et al. 2000). Another explanation may be related to the use of simple PTFs, which include a low number of explanatory variables (Nebel et al.

2010). In this particular study, the soils of the Caramacate River basin were classified as stony according to the rock fragment volume (containing over 35 or 40% in volume of soil particles larger than 2 mm) subjected to extensive grazing systems. This was one of the most distinct factors between the soils of the study area and the soils used to generate the aforementioned PTFs.

The equations developed by other researchers were developed for soils of alluvial origin, mainly agricultural. These functions are likely to allow finding a correct estimation of FC in most of fine soils but not in stony soils. Therefore, stoniness was considered as a possible explanation of the differences found between PTFs.

The PTFs developed by Urach's PTF (Reichert et al. 2009) and Bell and Van Keulen (1995) presented the largest values of R^2, respectively. In the literature, it is well-known that the soil bulk density is related to the soil structure and that it has been used to estimate the water content at − 33 kPa. Then, the equations that did not take into account the bulk density to estimate the water content at − 33 kPa had the worst behavior, which correspond with the findings by Nasri et al. (2015).

The PTFs did not show better efficiency for the set of soils that were tested, which confirmed the results obtained by Medeiros et al. (2014). We found a great variability in the behavior of the PTFs, which either overestimated or underestimated the water content. This occurred mainly because soils were heterogeneous and had different textural classes (Frison et al. 2009; Li et al. 2016). This variability in the results is higher in sandy and stony soils (Li et al. 2016). In those cases, PTFs may exhibit large differences when comparing predicted and in situ measured soil water content (Nasri et al. 2015). Therefore, the results of the present research agreed with those reported by Patil and Singh (2016), in the sense that a single function cannot be termed generic.

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Pedotransfer function to estimate soil water content at – 33 kPa in the study area

Once the outliers were removed from the soil data base of the study area, a correlation analysis between the soil water content at matric potential of − 33 kPa and all soil characteristics was performed (Table 5). The highest correlation coefficients were obtained for soil bulk density (− 0.81), sand (− 0.35), and RFV (− 0.23).

Table 5

Correlation analysis (R^2) between the gravimetric soil water content at matric potential of − 33
variables used in the generated pedotransfer function

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Correlation	Clay[a]	Silt[b]	Sand[c]	RFV1[d]	Clay2[e]	Silt2[f]	Sand2[g]	Bd[h]	SOM[i]	W
Clay	1.00	−0.21	− 0.25	− 0.18	0.84	0.00	− 0.39	0.13	0.04	0
Silt	−0.21	1.00	− 0.56	− 0.71	− 0.01	0.82	− 0.49	0.03	0.02	0
Sand	−0.25	0.14	1.00	0.07	− 0.38	−0.47	0.89	−0.12	0.18	−
RFV^2	−0.18	−0.71	0.07	1.00	− 0.16	−0.65	0.17	−0.03	−0.21	−
$Clay^2$	0.84	−0.01	− 0.38	− 0.16	1.00	0.29	− 0.12	0.43	−0.12	−
$Silt^2$	0.00	0.82	− 0.47	− 0.65	0.29	1.00	− 0.19	0.41	0.24	−
$Sand^2$	−0.39	−0.49	0.89	0.17	− 0.12	−0.19	1.00	0.20	0.12	−
Bd	0.13	0.03	− 0.12	− 0.03	0.43	0.41	0.20	1.00	0.07	−
SOM	0.04	0.02	0.18	− 0.21	− 0.12	0.24	0.12	0.07	1.00	−
WR_{-33kPa}	0.08	0.21	− 0.09	− 0.23	− 0.18	−0.11	− 0.35	−0.81	−0.12	1

~~*Clay*:, clay content (%)~~; ~~*Silt*, silt content (%)~~; ~~*Sand*, sand content (%)~~; ~~*RFV*, rock fragments (%); *Clay*^{2e} clay content (%) × Bd; *Silt*^{2f} silt content (%)~~ × ~~Bd; *Sand*^{2g} sand content (%)~~ × B ~~soil bulk density (Mg m^{-3})~~; ~~*SOM*, soil organic matter content (g kg^{-1})~~; ~~*WR*$_{-33 kPa}$, gravimet water content (kg kg^{-1}) at the matric potential of − 33 kPa~~ [a]Clay: clay content (%); [b]Silt: s content (%); [c]Sand: sand content (%); [d]RFV: Rock fragments volume (%); Clay2[e]= clay con (%)xBd; Silt2[f]= silt content (%)xBd; Sand2[g]= sand content (%)xBd; [h]Bd: soil bulk density ([i]SOM: soil organic matter content (g kg^{-1}); [j]WR-33kPa: gravimetric soil water content (kg k the matric potential of -33 kPa

The generated multivariate linear regression had a $R^2 = 0.65$ (Table 6). It was slightly higher than the R^2coefficient of the previously evaluated PTF of Reichert (2009) ($R^2 = 0.62$, Table 4), but the values of ME and RMSE were higher than those of Urach's PTF (Reichert et al. 2009).

Table 6

Generated pedotransfer function for estimating the gravimetric soil water content (kg kg^{-1}) at − 33 kPa in soils from Caramacate River Basin, Venezuela

Pedotransfer function	R^2	ME[e]	RMSE[f]
SWC = 0.809 − (0.40 × Bd[a]) − (0.037 × SOC[b]) − (0.001 × sand[c]) − (0.002 × RFV[d])	0.65	0.12	0.25

[a]*Bd*, soil bulk density (Mg m^{-3}); [b]*SOC*, soil organic carbon content (g kg^{-1}); [c]*Sand*, sand content (%); [d]*RFV*, rock fragments volume (%); [e]*ME*, mean error and [f]*RMSE*, root mean square error, in both case the values are expressed in kg kg^{-1}

Like other PTFs, the variables used to build the model can be determined easily. However, in addition to the commonly used variables (particle size distribution, bulk density, soil organic carbon, and soil organic matter), rock fragment volume was included as an important variable to try to characterize the stony soils.

In this respect, the inclusion of the rock fragment volume variable could have favored the results, since there are authors who attribute the differences between the content of measured and estimated soil water to the presence of stones (Coppola et al. 2013). The effect of the rock fragment volume was shown by Tetegan et al. (2015), who showed that failing to account for the rock fragments may lead to erroneous conclusions and unappropriated recommendations.

Other authors note that the available water content could be strongly misjudged when the rock fragments are not taken into account. This usually occurs because of the heterogeneity of soil structure (including macropores), which modify the pore space and, in turn, influences the saturated hydraulic conductivity (Nasri et al. 2015). Additionally, Tetegan et al. (2011) showed that soil available water content could be underestimated about 5 to 33%, depending on the lithology of the coarse elements.

This result is obvious in the case of stony soils, due to soil sampling not allowing collection of possible heterogeneities found on the field, a situation that is aggravated by inadequate reproduction of soil behavior in the laboratory (Coppola et al. 2013). However, the determination of a function of local pedotransference is a better approximation.

Conclusions

The present research showed the need to validate the PTFs to estimate soil water content developed in other locations, before applying them to different areas. Then, generation of equations fitting the characteristics of the soils of the study area is convenient, even with a low number of samples. In the case of the soils of the

Caramacate River basin, the Urach's PFT was the one with the best performance, although its precision (RMSE) was low. The other PTFs did not appear to be appropriate, possibly because mountain soils under study were rich in 2:1 clays (vermiculite and smectite) and high stoniness. Although the results could be improved by considering additional variables, using a pedotransfer function development within the study area would facilitate the estimation of parameters to be used in modeling of different types of processes.

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